# Red Team

# DARPA Grand Challenge Technical Paper

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# Introduction

This paper describes the Red Team's technical approach for competing in the DARPA Grand Challenge and addresses 37 items outlined in http://www.darpa.mil/grandchallenge/technicalpaper.doc.

These are divided among 3 sections: 'System Description', 'System Performance', and 'Safety & Environmental Impact'. The paper is limited to 10 single-sided pages, exclusive of any cover pages, diagrams, or attachments. Four Attachments describe the vehicle design. The original GC questions are in Attachment B. GC Review comments are in Attachment C.

# 1. System Description

## a. Mobility

The Red team's race vehicle, Sandstorm, is a M998 HMMWV vehicle modified for autonomous race driving (Figure 1).

**Figure 1: Sandstorm March 2004**

1. Ground contact is four wheels: 37" diameter, 12.5" width, 130" wheelbase, and 72" track width (see Figure 2). Widest part of vehicle is brush guard, 84”. Suspension is coil over socket, Figure 3.

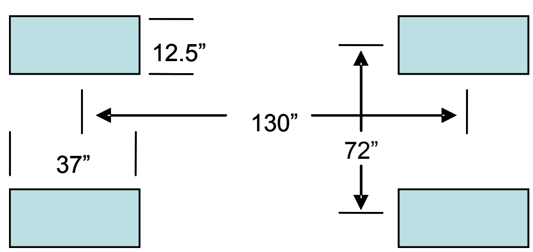


**Figure 2: Footprint dimensions**

**Figure 3: Suspension**

2. The vehicle is 4-wheel drive equipped, includes 4-wheel independent inboard disk brakes, and Ackermann steering for locomotion.

3. Wheels are actuated through the stock drive train powered by a 6.2 liter turbo-charged diesel engine. Electric actuators control steering, throttle, braking, and gear shifting. Sensor stabilization is controlled by electric motors.

## b. Power

1. The vehicle is powered by a 6.2 liter turbo-charged, diesel-fueled internal combustion engine. Vehicle electric bus is 24V alternator with dual series 12VDC lead-acid batteries. An auxiliary diesel generator provides payload power electrically filtered through lead-acid batteries.

2. Work is produced in two forms consisting of energy consumed as locomotive power and electrical consumption for vehicle computing, sensing and servo-mechanism systems.

3. At race start, the vehicle will hold sufficient diesel fuel to travel in excess of 300km.

## c. Processing

1. On-board vehicle computing systems defined as follows:

| Type | Function |
|---|---|
| Pentium III PC104 Stacks. | Drive by wire control and supervisory, sensor vector pointing. |
| Itanium 2 Based Server, 4 Processors. | Path Planning |
| Xeon Based Computer, Dual processors. | LIDAR and RADAR data acquisition, terrain analyses, stereo processes, map data management and data transfer to path planner. |

2. Perception perceived environmental interpretation is achieved by combining LIDAR, RADAR and stereovision range data. This data is then processed to synthesize a variety of maps used by vehicle logic to determine traversability. Obstacles are marked as high or infinite cost, while clear traverses are marked as low or no cost.

   Macro-route planning task is achieved by combining elevation topology, satellite imagery and ground truth data to form a single comprehensive global map. This map is then processed using a preplanning algorithm, generating a cost-map and route through areas of interest. Points on this route are then derived as goals for online planning.

   To facilitate synthesis of control arc and velocity, the algorithm considers multiple possible traversable arcs forward of vehicle position from the traversable space. Each possible arc is evaluated in terms of least cost to goal. The "best" path at any given interval is then communicated to the controller to command vehicle motion.

## d. Internal Databases

1. An off-board map database contains map features including sand, water, paved roads, unpaved roads, vegetation, rock, dry lake beds, out of bounds, and non-traversable terrain to the extent that they are known. This data comes from integrated USGS and BLM maps and is corrected relative to aerial imagery and road reconnaissance. During the two hour period prior to race, provided waypoints are used to extract relevant portions of this map database,

which is transferred to vehicle through a removable, wired connection. The distance from the external source to vehicle is within 150 feet.

## e. Environment Sensing

1. Perception sensors are listed in the table below with their primary functions, sensing horizon, and mode of operations.

| Sensor | Active/Passive | Primary Function |
|---|---|---|
| Long Range LIDAR line scanner, 1 each | Active | Terrain topology mapping, obstacle detection and characterization |
| LIDAR line scanner, 3 each | Active | Obstacle detection and geometry characterization |
| FMCW RADAR scanner | Active | Obstacle detection |
| Stereo video camera pair | Passive | Obstacle detection |

2. Various sensor mounting configurations and functionality control scenarios as listed below:

| | |
|---|---|
| LIDAR line scanner | 1. Vehicle roof mounted.<br>2. 3-axis stabilized platform mounted.<br>3. 3-axis pointing capability.<br>4. Custom interface controlled. |
| LIDAR line scanner | • Mounted left and right, front of brush guard.<br>5. Mounted below radar and stabilized in pitch.<br>6. Controlled through RS422. |
| RADAR scanner | • Mounted on the front of the E-box on a single axis stabilized platform operating in the pitch axis.<br>7. Shock/vibration isolated hard-mount.<br>8. Ethernet controlled. |
| Stereovision camera pair | • Vehicle roof mounted.<br>9. 3-axis stabilized platform mounted.<br>10. 3-axis pointing capability.<br>11. Custom interface controlled. |

## f. State Sensing

1. Vehicle state is sensed via optical encoders, potentiometers, rotational variable differential transformers (RVDT), current and voltage sensors. Vehicle state is reported by GPS (latitude, longitude, and altitude), vehicle Pose (roll, pitch, yaw), and vehicle velocity. Onboard software calculates vehicle's speed and acceleration.

2. Vehicle state sensors feed Vehicle Health, which produces a summary for Race Logic. The latter selects an appropriate race mode to guide control of the vehicle.

## g. Localization:

1. Vehicle localization is achieved via GPS/INS based Position & Orientation System, which globally estimates vehicle position and orientation with respect to map database.

2. The Position & Orientation System (POS) integrates last known vehicle position, encoded vehicle motion using a distance measurement indicator (DMI), and inertial navigation sensors (INS) to estimate and update vehicle position and orientation.

3. Areas outside the Grand Challenge Route boundaries are registered 'non-traversable' on the internal map database. The vehicle path-planning algorithm will not direct the vehicle to traverse regions registered as 'non-traversable'.

4. Applanix POS unit is utilized for inertial/GPS/DMI instrumentation. The Applanix POS system is a strapdown inertial navigation platform, featuring high-bandwidth, low-latency, Kalman filtering, GPS with azimuth measurement, distance measurement indicator (DMI). Applanix platform calculates vehicle position and orientation data with excellent short-term accuracy and minimum long-term drift. Applanix POS platform provides dynamically accurate, high-bandwidth full-kinematic vehicle state measurements, and provides motion compensation information to other sensor systems onboard the Grand Challenge vehicle.

## h. Communications

1. Prior to the race, pit crew to vehicle communications will utilize 802.11b/g wireless network and CAT5 Ethernet cable for debugging and setup.
2. At the race starting line, the 802.11b/g wireless communication network and the CTA5 Ethernet cable shall be removed prior to race start. Final instructions to the vehicle are communicated via CAT5 Ethernet cable.
3. During the race, vehicle will only receive DARPA E-Stop and Pause, GPS, and commercially available DGPS corrections via satellite.

## i. Non-autonomous control

The vehicle will remain human drivable. The vehicle will also be controllable through a wireless Ethernet connection. The wireless Ethernet Bridge shall be removed prior to the race.

# 2. System Performance

## a. Previous Tests

Extensive testing and evaluation was conducted to evolve vehicle sensing and autonomous steering capability. Test and evaluation demonstrated object and obstacle detection as well as proof-of-concept associated with perception sensing capabilities. Initial vehicle implemented integrated differential GPS, three LIDAR scanners and a video camera. Combining GPS, IMU and LIDAR data facilitated building of 3D point-clouds showing obstacles, vegetation, and roads. Post-processing synthesized goodness-maps and facilitated run-simulations in addition to physical testing. Both wireless and mechanical E-stop systems were implemented and tested. Although the wireless E-stop was not specific unit provided by GC officials, proof of concept was successful. E-box cooling system was designed and implemented, based on analyzed and measured thermal characteristic data. E-box shock isolation system was designed and implemented, based on analyzed and measured dynamic inertial data. DARPA GC E-stop system was also implemented and verified functional.

## b. Planned Tests

Incremental testing regime will continue as program develops and moves towards higher navigational speeds, more complex real-time processing, and increased sensing capability. Vehicle testing programs will include component, subsystem, speed, and desert local.

# 3. Safety and Environmental Impact

## a. Vehicle Top Speed

The vehicle has a top speed adequate to complete the prescribed course within the allotted duration.

## b. Vehicle Range

The vehicle has a range in excess of prescribed course.

## c. Safety Equipment

The safety equipment on-board the Challenge Vehicle is listed below.

1. Fuel containment: Fuel line cutoff solenoid connected to the disable E-Stop.
2. Fire suppression: Fuel valve cutoff and multiple fire extinguishers mounted external to the vehicle.
3. The fire extinguishers shall be removed prior to registering for QID.
4. Audio and visual warning devices**:** Klaxon, warning strobe, and brake lights in compliance with DARPA requirements.

## d. E-Stops

1. While the normal e-stop signal is active, the vehicle controller will remain in an inhibited state, ignoring all higher-level control inputs. In this inhibited state, all electronics and actuators remain powered, and the engine continues to run, but the vehicle will not move. Upon release of the normal E-Stop signal, the vehicle controller returns to its normal operating state, accepting control input from higher level planning modules. The disable e-stop causes a normally open relay to actuate. This causes the vehicle engine to shutdown and the service brake is fully engaged, effecting the vehicle to an abrupt halt. Field personnel

will unlock the brakes by throwing a clearly labeled pneumatic lever switch to the 'OVERRIDE' position that will release the parking brake, rotate a clearly labeled selector witch to the 'DISABLED' position to cut power to control motor, and pull a clearly labeled cord that moves the service brake actuator off the brake pedal. The auxiliary generator will continue to run but can in no way cause the vehicle to move.

2. Manual e-stop switches are of industrial grade. E-stop switches are placed on left and right side amidships and placed on each corner of the vehicle for total of six (6) units. The six manual E-stop switches are wired in series and inclusive to the wireless disable E-stop signal line. This will cause the manual E-stop switches to behave in exactly the same way as the wireless disable E-stop signal.

3. The vehicle is placed in neutral by shifting the transfer case lever to the 'neutral' position. However, due to the automatic transmission the vehicle can be moved without placing the transmission or transfer case in neutral. In addition, field personnel will be required to complete four steps:
    a. Throw a clearly labeled pneumatic lever switch to the "OVERRIDE" position;
    b. Move the "Brake/Throttle Actuator Switch" to the disable position
    c. Pull a clearly labeled cord to disable the safety brake function.
    d. Mount the 11" quick release removable steering wheel.

## e. Radiators

1. The devices on the Challenge Vehicle that actively radiate EM energy are listed below.

- Long Range LIDAR line scanner
- Short Range LIDAR line scanner
- RADAR scanner
- Vehicle and DARPA operational lights

3. The devices on the vehicle that can be considered hazardous to human eye or ear safety are listed below with their OSHA classification.

- Long Range LIDAR line scanner – OSHA Class 1 eye safe.
- Short Range LIDAR line scanner – OSHA Class 1 eye safe.
- RADAR scanner – ETSI Class 1 radiator.

4. The following safety measures are important regarding the radiators.

- Avoid standing in close proximity to RADAR platform.
- Avoid looking directly at LIDAR scanner.

- Avoid looking at rotating beacon and wear audio protection during vehicle operations

## f. Environmental Impact

1. When a tire flat occurs, the run flat inserts are non-metal and keep the metal rims from contacting the paved roadway.

2. The maximum ground pressure is 32psi while tire are inflated.

3. Engine crankcase, engine cooling system, transmission and transfer case, differential gear housings, power steering and hydraulic brake system, and fuel tank contain various fluids, which pose a potential threat to the environment.